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Energy Conversion and Management 101 (2015) 136–150

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Life-cycle impacts from novel thorium–uranium-fuelled nuclear energy systems

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ARTICLE INFO

Article history:
Received 1 October 2014
Accepted 14 April 2015
Available online 2 June 2015

Keywords:
Thorium
Uranium
Monazite
Life-cycle analysis
Nuclear energy

ABSTRACT

Electricity generated from nuclear power plants is generally associated with low emissions per kWh generated, an aspect that feeds into the wider debate surrounding nuclear power. This paper seeks to investigate how life-cycle emissions would be affected by including thorium in the nuclear fuel cycle, and in particular its inclusion in technologies that could prospectively operate open Th–U-based nuclear fuel cycles. Three potential Th–U-based systems operating with open nuclear fuel cycles are considered: AREVA's European Pressurised Reactor; India's Advanced Heavy Water Reactor; and General Atomics' Gas-Turbine Modular Helium Reactor. These technologies are compared to a reference U-fuelled European Pressurised Reactor. A life-cycle analysis is performed that considers the construction, operation, and decommissioning of each of the reactor technologies and all of the other associated facilities in the open nuclear fuel cycle. This includes the development of life-cycle analysis models to describe the extraction of thorium from monazitic beach sands and for the production of heavy water. The results of the life-cycle impact analysis highlight that the reference U-fuelled system has the lowest overall emissions per kWh generated, predominantly due to having the second-lowest uranium ore requirement per kWh generated. The results highlight that the requirement for mined or recovered uranium (and thorium) ore is the greatest overall contributor to emissions, with the possible exception of nuclear energy systems that require heavy water. In terms of like-for-like comparison of mining and recovery techniques, thorium from monazitic beach sands has lower overall emissions than uranium that is either conventionally mined or recovered from in-situ leaching. Although monazitic beach sands (and equivalent placer deposits) only form 30% of the overall known thorium ore deposits, it is expected that such deposits would generally be utilised first if thorium becomes a viable nuclear fuel. Overall, for these four nuclear energy technologies, the range of CO_2(eq) emissions per kWh generated (6.60–13.2 gCO_2(eq)/kWh) appears to be low in comparison to the majority of electricity-generating technologies.

1. Introduction

The debate surrounding nuclear power is often clouded by somewhat strong and divergent opinions. Electricity generated from nuclear power plants is generally associated with low emissions per kWh generated. However, issues surrounding the wastes, economics, safety, the potential for proliferation and diversion of nuclear materials impact the social and environmental acceptability of such technologies.

At present open nuclear fuel cycles, i.e. those where the fuel is utilised once, are generally more prevalent than reprocessing-based closed nuclear fuel cycles. This is observed to be due to economic costs and a tendency to greater resistance against theft and diversion of spent nuclear fuel and separated special nuclear materials. However, the penalty in only utilising the nuclear fuel once is that a significant demand is placed on uranium ore reserves. From estimates published in 2012, there are 5.33×10^6 tonnes of uranium recoverable for less than US $\$130/kg_U$ [1]. Estimates for total uranium ore reserves (including unconventional resources but excluding uranium found in seawater) range from 1.92×10^7 tonnes [2] to 3.93×10^7 tonnes [3]. At 2012 consumption rates of 67,990 tonnes of uranium per year [4], the reserve of 5.33×10^6 tonnes would last for another ~80 years and the reserve of 3.93×10^7 tonnes would last for ~600 years —although uranium consumption rates are expected to increase over time as more nuclear power plants are constructed. This compares to fully closed

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http://dx.doi.org/10.1016/j.enconman.2015.04.041
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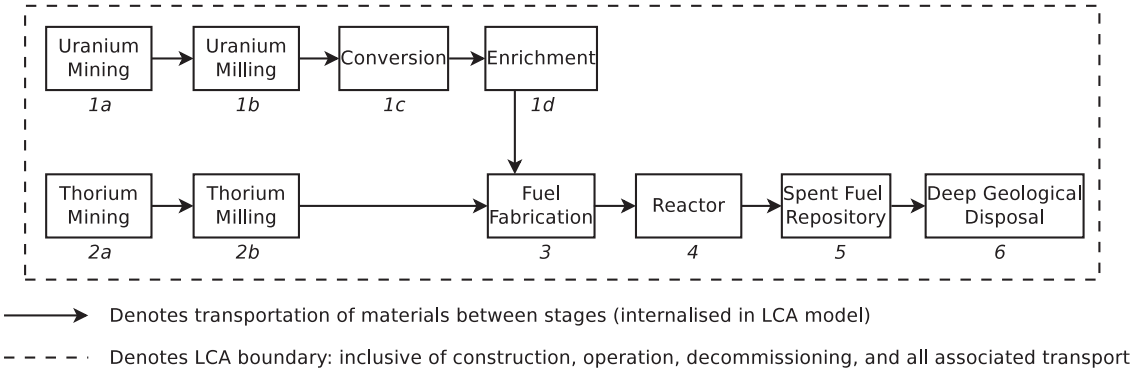

Fig. 1. Stages of the open nuclear fuel cycle considered within this LCA. The construction, operation and decommissioning and transport requirements of each stage are considered.

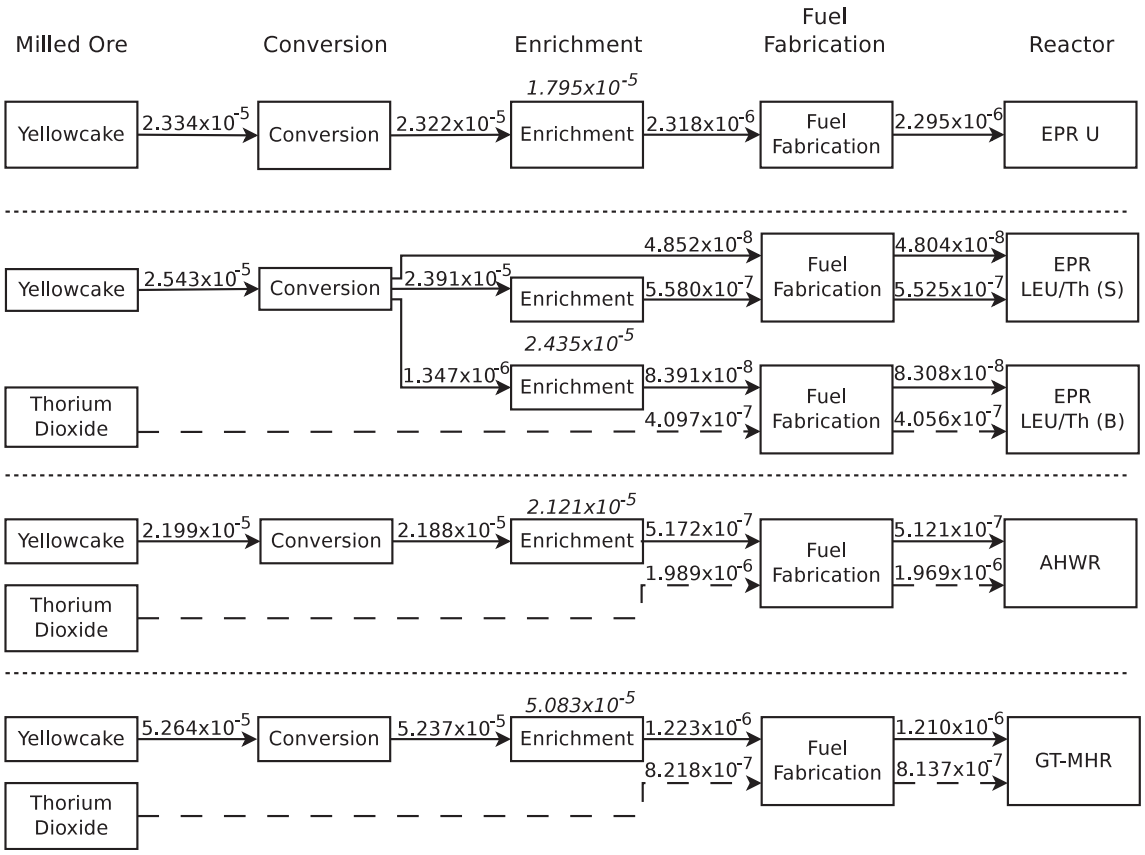

Fig. 2. Material flow diagrams describing the mass flows (in units of kg_{HM}) of uranium and thorium, required per kWh, for the four nuclear energy technology options analysed in this work. Uranium mass flows are depicted by black solid lines whereas thorium mass flows are depicted by black dashed lines. Italicised text denotes the separative work units required per kWh. Figure taken from Ref. [11]. N.B. EPR LEU/Th (S) and EPR LEU/Th (B) are individual components of the Th–U-fuelled EPR.

nuclear fuel cycles where ore resources could be extended to beyond 10,000 years [5].

Thorium, an element that is lighter than uranium, has been proposed as a potential nuclear fuel of the future, with suggestions that it could extend the supply of nuclear fuel, and have significant economic, radiotoxicity, and proliferation resistance advantages over conventional uranium-based fuels [6]. The most recent estimates of thorium reserves range from 6.5×10^6 to 7.4×10^6 tonnes (ignoring resource categories and cost classes) [7], although from a geological standpoint thorium is expected to be 3–4 times more abundant than uranium in the continental crust [8].

Table 1
Breakdown of the amounts of uranium mined and corresponding mining techniques for 2013 (values from Ref. [20]).

Mining technique	Tonnes U	%
Conventional underground	17,198	29
Conventional open-pit	10,977	18
In-situ leaching	27,496	46
By-product[a]	3966	7

[a] ~88% of the by-product comes from the Olympic Dam iron oxide–copper–gold deposit in Australia.

Table 2
Projected share of technology used in enriching uranium from Ref. [22].

Supply source	2000 (%)	2010 (%)	2017 (projected) (%)
Diffusion	50	25	0
Centrifuge	40	65	93
Laser	0	0	3
Highly-enriched uranium ex weapons	10	10	4

Table 3
Breakdown of present global thorium reserves, as detailed in Ref. [7].

Deposit type	Relative abundance (%)
Carbonatite	37
Placer	30
Vein	20
Peralkaline rocks	10
Others	3

Whilst the adoption of thorium has traditionally been associated with reprocessing-based "closed" nuclear fuel cycles [9], open nuclear fuel cycles when compared to closed nuclear fuel cycles have: (1) significantly lower fuel cycle costs; (2) lower infrastructure requirements; (3) greater resistance against nuclear weapons proliferation; and (4) enhanced protection against diversion and theft. Therefore, an open question remains as to whether thorium can successfully be included within future open nuclear fuel cycles. A recent review paper [10] has highlighted a number of technology families that could prospectively use open Th–U-based fuel cycles, including: (1) existing light water reactors (LWRs), (2) novel heavy-water-moderated, light-water-cooled reactors, and (3) novel high-temperature gas-cooled reactors. Fuel cycle modelling of three nuclear energy technologies operating with open Th–U-based fuel cycles has recently been performed [11]. The reactor technologies considered in Ref. [11]: AREVA's European Pressurised Reactor (EPR), the Indian Advanced Heavy Water Reactor (AHWR), and General Atomics' Gas-Turbine Modular Helium Reactor (GT-MHR),

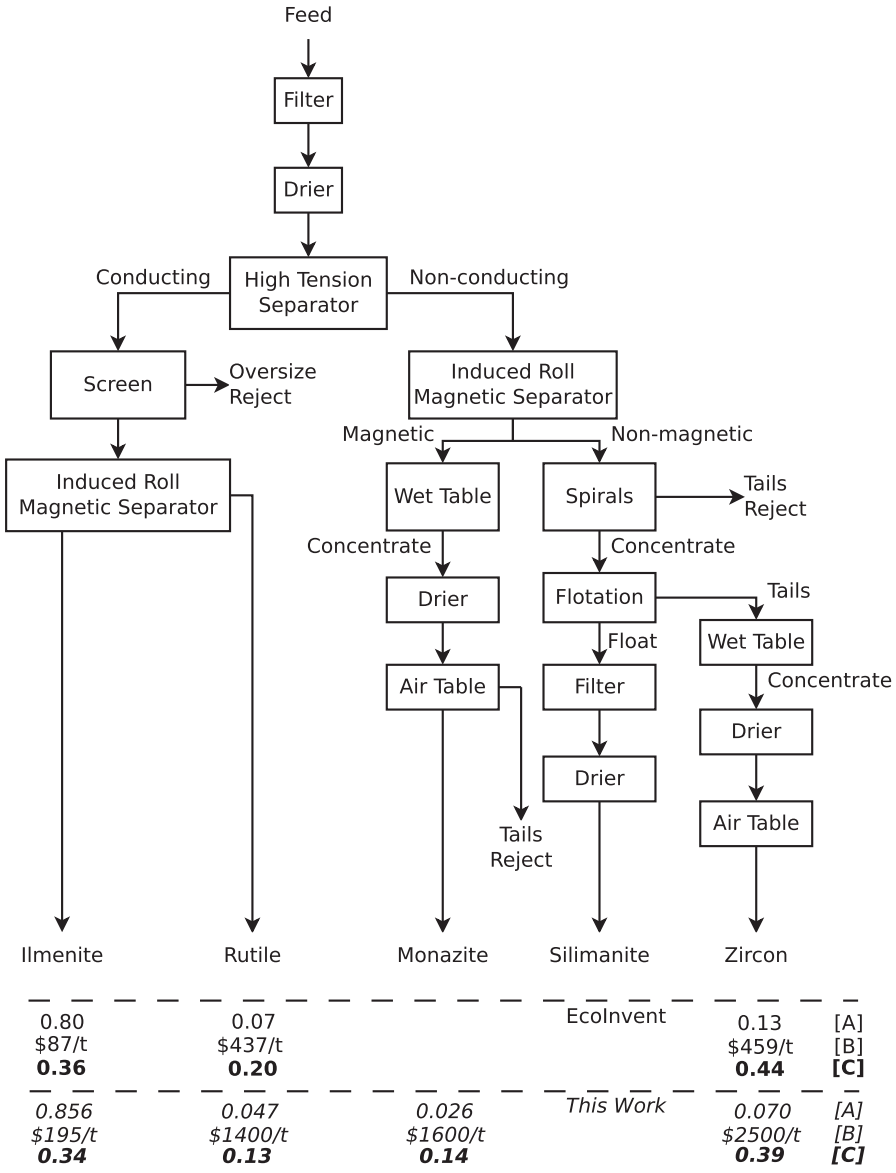

Fig. 3. Flow sheet for the production of monazite, adapted from Ref. [25]. [A] denotes the relative abundance of the mineral; [B] denotes the economic value of the mineral; and [C] denotes the normalised weight from the product of [A] and [B]. Original data used for the EcoInvent weighting are presented in normal text with the weightings used (derived from 2011 US) values in Ref. [26]) in italic text.

represent each of the three aforementioned technology families. A natural extension of this modelling is to assess the life-cycle emissions of these technologies together with the life-cycle impacts of producing thorium-based nuclear fuels. In addition to these systems, novel designs of today's nuclear energy technologies (such as the Reduced-Moderation Boiling Water Reactor [12]) or the use of reprocessing-based nuclear fuel cycles in advanced Generation IV technologies [13] appear to be the only ways in which thorium may be more advantageous on a large scale. Thorium-based fuel may also find utility in the more niche application of the disposition of stockpiles of separated plutonium arising from the reprocessing of spent nuclear fuel or the decommissioning of nuclear weapons [14], though such reprocessing-based fuel cycles are outside the scope of this present work.

This paper looks at what the life-cycle impacts of including thorium into the nuclear fuel cycle would be and includes a comparative life-cycle assessment (LCA) of three nuclear energy systems that could potentially utilise open thorium–uranium-based nuclear fuel cycles. These three systems are: AREVA's European Pressurised Reactor (EPR), a light water reactor technology; India's Advanced Heavy Water Reactor (AHWR), a heavy-water-moderated, light-water-cooled reactor technology; and General Atomics' Gas-Turbine Modular Helium Reactor (GT-MHR), a high-temperature gas-cooled reactor technology. The reference technology used to compare these three thorium–uranium-fuelled technologies is an EPR fuelled with low-enriched uranium (LEU). Further details on the specifics of each reactor technology are contained in Section 2.7 and Ref. [11]. Section 2 covers the stages of the open nuclear fuel cycle and the relevant processes considered for the life-cycle assessment from either the EcoInvent v2.2 database [15] or from other literature. The results of the life-cycle impact assessment of these technologies are presented in Section 3 and consider the main atmospheric emissions per kWh generated, namely 100-year global warming potential, acidification potential, eutrophication potential, and steady-state ozone depletion potential. A discussion of the results, along with the basis for focussing on atmospheric emissions and the limitations of this study, is presented in Section 4. Concluding remarks are presented in Section 5.

2. LCA of open nuclear fuel cycle stages

The open nuclear fuel cycle that forms the basis of this study is presented in Fig. 1. It should be noted that the system boundaries include construction, operation, and decommissioning of each stage with transportation requirements internalised for each stage; the functional unit of per kWh generated is used to compare these nuclear energy systems and per kg produced for heavy water production and also for the mined/recovered uranium and thorium; and that Stages 1–2 and 5–6 are the same for all four nuclear energy systems that are being studied here. Differences in the fuel fabrication processes and reactors are reported in Sections 2.6 and 2.7. The basis for the LCA model is taken from Ref. [16], and the similarities and differences between that LCA model and the one used in this work are presented in Sections 2.2–2.8.

Due to the large number of processes contained within each stage of the nuclear fuel cycle and the variation in uncertainties associated with each process, the results contained in Section 3 comprise individual values for each stage of the nuclear fuel cycle (presented in graphical form) with a single value for each emission type per functional unit.

Table 4
Bill of materials for producing 1 kg of monazite from beach sands. Input and output materials are based on mining of beach sands for zircon as described in Ref. [24]. Plain text denotes processes (and terminology) within the EcoInvent v2.2 database. Italic text denotes processes that are not in the EcoInvent v2.2 database and which therefore have been determined by the authors.

Input materials from EcoInvent	Quantity and units
Thorium dioxide, 6% in monazite, in ground (AU)	*6.000×10^{-2} kg*
Electricity, medium voltage, production UCTE, at grid (UCTE)	1.642 kWh
Recultivation, bauxite mine (GLO)	1.454×10^{-2} m^2
Transformation, to mineral extraction site	1.454×10^{-2} m^2
Transformation, from pasture and meadow	8.723×10^{-3} m^2
Transformation, from forest	5.815×10^{-3} m^2
Occupation, mineral extraction site	1.454×10^{-1} m^{2}a
Water, well, in ground	9.477×10^{-2} m^3
Hard coal, burned in industrial furnace 1–10 MW (RER)	6.462 MJ
Diesel, burned in building machine	2.800 MJ
Natural gas, burned in industrial furnace >100 kW (RER)	1.938 MJ
Heavy fuel oil, burned in industrial furnace 1 MW, non-modulating (RER)	6.462×10^{-1} MJ
Mine, bauxite	2.150×10^{-9} number of pieces
Output materials from EcoInvent	**Quantity and units**
Monazite, 6% thorium dioxide, at plant (AU)	*1 kg*
Heat, waste	5.923 MJ
Particulates, >10 μm	7.808×10^{-4} kg
Particulates, >2.5 μm, and <10 μm	4.038×10^{-4} kg
Suspended solids, unspecified	2.477×10^{-4} kg
Particulates, <2.5 μm	1.615×10^{-4} kg
Iron, ion	1.2×10^{-5} kg
^{232}Th	1.163×10^{-2} kBq
^{226}Ra	3.085×10^{-4} kBq
^{238}U	8.990×10^{-5} kBq

Table 5
Bill of materials to produce 1 kg of ThO_2 from monazite. Input materials are based on Ref. [27] with energy requirements based on EcoInvent's LCA for bastnasite production, scaled by a factor of 0.01 as posited by Ref. [28]. Plain text denotes processes (and terminology) within the EcoInvent v2.2 database. Italic text denotes processes that are not in the EcoInvent v2.2 database and which therefore have been determined by the authors.

Input materials from EcoInvent	Quantity and units
Monazite, 6% thorium dioxide, at plant (AU)	*1.762×10^{1} kg*
Chemicals inorganic, at plant (GLO)	1.986×10^{-2} kg
Chemicals organic, at plant (GLO)	1.986×10^{-2} kg
Barite, at plant (RER)	2.106×10^{-1} kg
Chemical plant, organics (RER)	9.000×10^{-9} unit
Hydrochloric acid, 30% in H_2O, at plant (RER)	8.600×10^{-2} kg
Hydrogen peroxide, 50% in H_2O, at plant (RER)	2.140×10^{-2} kg
Nitric acid, 50% in H_2O, at plant (RER)	2.157 kg
Sodium hydroxide, 50% in H_2O, production mix, at plant (RER)	4.068×10^{-1} kg
Sulphuric acid, liquid, at plant (RER)	5.689×10^{-1} kg
Quicklime, milled, loose, at plant (CH)	1.242 kg
Silica sand, at plant (DE)	6.150×10^{-2} kg
Electricity, medium voltage, production UCTE, at grid (UCTE)	4.560×10^{-3} kWh
Disposal, non-sulfidic tailings, off-site (GLO)	9.690×10^{-1} kg
Disposal, sulfidic tailings, off-site (GLO)	1.248 kg
Transport, lorry >16 t, fleet average (RER)	1.001 t km
Heavy fuel oil, burned in industrial furnace 1 MW, non-modulating (RER)	1.920×10^{-2} MJ
Water, unspecified natural origin	2.080×10^{-2} m^3
Output materials from EcoInvent	**Quantity and units**
^{226}Ra (air unspecified)	6.19×10^{1} kBq
^{228}Ra (air unspecified)	4.464×10^{2} kBq
^{232}Th (air unspecified)	1.016×10^{1} kBq
Heat, waste	1.642×10^{-2} MJ
Thorium dioxide, at plant (AU)	*1 kg*

Section 2.1 details the uranium and thorium material flows and separative work requirements that interlink Stages 1–6 for the four different options that are being studied in this work. This summarises the results from Ref. [11] which are relevant for the LCA analysis.

It is noted that within the tabulated data contained in this paper, the following abbreviations, as adopted by EcoInvent, are used to represent the following countries and/or regions: (AU) denotes Australia, (CH) denotes Switzerland, (RER) denotes Europe, (GLO) denotes global, and (UCTE) denotes the electricity supply mix of the European network.

2.1. Material flows for uranium, thorium, and separative work requirements

Uranium, thorium, and separative work requirements for the four different nuclear fuel cycles have been determined using reactor physics modelling techniques and the UK National Nuclear Laboratory fuel cycle modelling code "ORION" [17]. Further details on the methodologies used to calculate these material flows are contained in Ref. [11]. The required uranium, thorium, and separative work units (per kWh generated) for each of the four systems are presented in Fig. 2 and formed the primary structure of each LCA. Details on how the mined uranium ore corresponds to the required milled ore (Stages 1a and 1b) are presented in Section 2.2, with conversion (Stage 1c) and enrichment (Stage 1d) processes described in Sections 2.3 and 2.4 respectively. Details on how thorium-rich monazite sands are mined and processed (Stages 2a and 2b) are contained in Section 2.5. The treatment of spent nuclear fuel (Stages 5 and 6) is described in Section 2.8.

2.2. Stages 1a & 1b: Uranium mining and milling

Within Ref. [16], three mining techniques are considered: conventional open-pit mining, conventional underground mining, and in-situ leaching (ISL) (also termed in-situ recovery). The allocation of each technique is 25%, 25% and 50% respectively. In this work, the same allocations are assumed. This compares to the market share for each mining technique in 2013 as shown in Table 1. The LCA data for conventional open-pit mining and conventional underground mining comes from Ref. [18], whereas the LCA data for ISL comes from Ref. [19]. A global uranium content of 0.134% in the mined ore has been adopted in this work, with losses in mined ore assumed to be 5%.

2.3. Stage 1c: Conversion

Only the wet uranium-nitrate-hexahydrate conversion process to transform U_3O_8 ("yellowcake") into UF_6 from Ref. [18] is considered in this work. In 2013, the wet process accounted for ~80% of global uranium conversion capacity [21].

2.4. Stage 1d: Enrichment

Historically, two families of technologies have been used for enriching uranium: (1) gaseous diffusion, e.g. USEC, Paducah (KY, USA) and (2) gas centrifugation, e.g. URENCO (Capenhurst), UK. Gaseous diffusion has now become obsolete: Areva's Georges Besse gaseous-diffusion facility in Tricastin (France) has been replaced by the Georges Besse II centrifuge enrichment plant, and the USEC gaseous-diffusion plant in Paducah was shut down in mid-2013. Predictions of the future breakdown of enrichment technologies from the World Nuclear Association are shown in Table 2. In this work, only URENCO centrifuge enrichment is considered, the LCA for which is contained in Ref. [18].

2.5. Stages 2a & 2b: Thorium mining and milling

As mentioned in Section 1, present thorium reserves are estimated to be in the range $6.5–7.4 \times 10^6$ tonnes. A breakdown of the types of deposit is shown in Table 3.

Thorium is typically treated as a waste by-product of rare-earth-element (REE) mining and processing; hence,

Table 6
Materials that comprise the total amount of fabricated fuel (and other supporting structures) contained in the core of each reactor technology. For all four nuclear energy systems, the quantities of uranium, thorium, and burnable poisons (Gd_2O_3/Er_2O_3) were calculated by the authors from data provided in Ref. [11]. Details provided in the footnotes are explained further in Section 2.6.

Material	EPR UO_2 (kg)[a]	EPR UO_2/ThO_2 (kg)[a,b]	AHWR UO_2/ThO_2 (kg)[c]	GT-MHR UO_2/ThO_2 (kg)[d]
Uranium (heavy metal)	1.27×10^5	4.77×10^4	6.73×10^3	1.04×10^4
Thorium (heavy metal)	–	7.04×10^4	4.50×10^4	7.97×10^3
Zircaloy	3.90×10^4	–	1.78×10^4	–
Inconel	1.04×10^3	1.04×10^3	3.53×10^2	–
SiC fuel cladding	–	1.91×10^4	–	–
AISI 304L stainless steel	3.52×10^3	3.52×10^3	2.15×10^3	–
Aluminium oxide	1.45×10^2	1.45×10^2	4.82×10^1	–
Boron carbide (B_4C)	4.37×10^2	4.37×10^2	2.61×10^3	7.89×10^2
Silver	1.20×10^3	1.20×10^3	–	–
Indium	2.25×10^2	2.25×10^2	–	–
Cadmium	7.49×10^1	7.49×10^1	–	–
Gadolinium (Gd_2O_3) or erbium (Er_2O_3)	2.08×10^2	8.88×10^1	1.09×10^2	–
Graphite	–	–	–	1.00×10^5
Carbon	–	–	–	3.09×10^3
Pyroclastic carbon	–	–	–	4.90×10^3
Zirconium carbide	–	–	–	8.69×10^3

[a] All "structural" materials (except uranium, thorium, and Gd_2O_3/Er_2O_3) were taken from Ref. [29].
[b] The differences in the quantities of zircaloy and SiC fuel cladding, as explained in Section 2.6, were calculated by the authors.
[c] The quantities of structural materials required for the AHWR were calculated by the authors by scaling the structural materials for the EPR in proportion to the assembly dimensions of the AHWR provided in Ref. [11]. The quantity of B_4C was directly calculated using data in Ref. [11].
[d] The quantities of structural materials required for the GT-MHR were calculated by the authors from Ref. [11].

Table 7
Estimates of the aggregated bill of materials for the three different nuclear reactors studied in this work. Details provided in the footnotes are explained further in Section 2.7.

EcoInvent material/process	Unit	Location	EPR[a,d]	AHWR[b,e]	GT-MHR[c,e]
Aluminium, primary, at plant	kg	RER	9.76×10^4	7.67×10^4	5.77×10^3
Chromium steel 18/8, at plant	kg	RER	1.24×10^7	1.39×10^6	1.39×10^7
Copper, at regional storage	kg	RER	5.38×10^5	3.95×10^5	1.01×10^5
Disposal, concrete, 5% water, to inert material landfill	kg	CH	6.83×10^8	4.55×10^8	6.83×10^7
Drawing of pipes, steel	kg	RER	1.83×10^6	5.13×10^5	–
Graphite, at plant	kg	RER	–	–	5.05×10^5
Hot rolling, steel	kg	RER	1.77×10^7	2.51×10^6	1.38×10^7
Polycarbonate, at plant	kg	RER	2.55×10^4	2.04×10^4	8.56×10^2
Polyester resin, unsaturated, at plant	kg	RER	6.27×10^3	5.02×10^3	1.92×10^2
Polyethylene, HDPE, granulate, at plant	kg	RER	1.27×10^5	1.01×10^5	8.52×10^3
Polymethyl methacrylate, beads, at plant	kg	RER	1.45×10^5	1.16×10^5	3.30×10^4
Polyvinylchloride, at regional storage	kg	RER	1.27×10^5	1.02×10^5	9.85×10^2
Reinforcing steel, at plant	kg	RER	5.09×10^7	9.14×10^6	4.04×10^6
Sheet rolling, aluminium	kg	RER	9.58×10^4	7.67×10^4	5.77×10^3
Sheet rolling, chromium steel	kg	RER	–	6.45×10^5	–
Sheet rolling, steel	kg	RER	4.69×10^5	3.76×10^5	3.76×10^5
Steel, low-alloyed, at plant	kg	RER	5.96×10^6	5.21×10^5	3.84×10^5
Synthetic rubber, at plant	kg	RER	3.00×10^4	2.40×10^4	1.12×10^3
Tin, at regional storage	kg	RER	3.45×10^4	2.76×10^4	1.74×10^3
Wire drawing, copper	kg	RER	4.52×10^5	3.28×10^5	8.40×10^4
Electricity, medium voltage, production UCTE, at grid	kWh	UCTE	9.55×10^8	6.37×10^8	9.55×10^7
Welding, arc, steel	m	RER	–	–	5.00×10^4
Concrete, normal, at plant	m^3	CH	3.89×10^6	2.80×10^5	4.70×10^4
Excavation, hydraulic digger	m^3	RER	3.48×10^5	2.32×10^5	6.54×10^4
Excavation, skid-steer loader	m^3	RER	3.48×10^5	2.32×10^5	6.54×10^4
Sawn timber, hardwood, planed, kiln dried, $u = 10\%$, at plant	m^3	RER	8.29×10^0	6.63×10^0	2.37×10^{-1}
Diesel, burned in building machine	MJ	GLO	3.42×10^8	2.28×10^8	3.42×10^7
Light fuel oil, burned in industrial furnace 1 MW, non-modulating	MJ	RER	2.57×10^8	1.71×10^8	2.57×10^7
Transport, freight, rail	tkm	CH	1.47×10^7	3.96×10^6	1.14×10^6
Transport, freight, rail	tkm	RER	1.37×10^7	9.12×10^6	1.37×10^6
Transport, lorry > 32 t, EURO5	tkm	RER	2.03×10^7	1.35×10^7	2.03×10^6
Transport, lorry 16–32 t, EURO5	tkm	RER	3.39×10^7	2.05×10^7	3.88×10^6

[a] Quantities of construction materials shown for the EPR was based off of the LCA model used in Ref. [16], amended as appropriate by the most recent construction estimates provided in Ref. [37].
[b] Quantities of construction materials shown for the AHWR were adapted from Refs. [38,39,42].
[c] Quantities of construction materials shown for the GT-MHR were, in part, calculated from drawings in Ref. [40], and also adapted from Ref. [42].
[d] Process energies required to construct the EPR were estimated by the authors from upscaling the process energy requirements used in the LCA model of Ref. [16] with respect to the additional material requirements in Ref. [37].
[e] Process energies were estimated by the authors from scaling the process energy required for the EPR.

Table 8
Material required to generate 1 kg of heavy water, adapted from Ref. [45]. Italic text denotes processes that are not in the EcoInvent v2.2 database and which therefore have been determined by the authors.

Input materials from EcoInvent	Quantities and units
Electricity, medium voltage, production UCTE, at grid (UCTE)	6.04×10^2 kWh
Steam, for chemical processes, at plant (RER)	5.660×10^3 kg
Heavy-water plant	*8.333×10^{-8} unit*
Hydrogen sulphide, H_2S, at plant (RER)	6.6×10^{-1} kg
Water, cooling, unspecified natural origin	24 m^3
Water, river	125 m^3
Output materials from EcoInvent	Quantities and units
Heavy water, from distillation-GS	*1 kg*

low-thorium-content ores for REE processing are presently favoured. Two distinct approaches are taken towards mining rare-earth elements: the first involves hard rock mining of ores, most notably bastnasite that is mined in China; the second involves separation of minerals from placer deposits, such as beach sands, most notably monazite that is extracted in India. This LCA will only consider monazite from placer deposits as the source of thorium in these nuclear fuel cycles. The rationale for this is that some of the largest concentrations of monazite can contain significant amounts of thorium (up to ~8 wt% content [23]), and that the co-produced rare-earth elements will offer additional economic incentive (i.e. there would initially not be economic incentive to mine solely thorium-based ores such as thorite). Assuming that thorium-rich monazite ores will be mined first, the thorium content has been assumed to be 6%.

The processing of beach sands is currently performed to extract other valuable minerals such as ilmenite, rutile, and zircon. Within EcoInvent v2.2, an LCA exists for the processing of zircon, ilmenite and rutile from beach sands in Australia [24]. This has been amended to include monazite by using the weightings for monazitic beach sands from India from Ref. [25] and weighting these in relation to their economic value (using 2011 US $ values provided in Ref. [26]). A flow diagram showing the processes involved in extracting monazite from beach sand, and the weightings used in this work, is presented in Fig. 3. The main data included in the LCAs for obtaining monazite from beach sands are presented in Table 4.

Table 9
Assumed materials required to construct a heavy-water plant. Inventory based on reported values in Ref. [46] for the decommissioning of Bruce Heavy Water Plant. Italic text denotes processes that are not in the EcoInvent v2.2 database and which therefore have been determined by the authors.

Input materials from EcoInvent	Quantities and units
Concrete, normal, at plant (CH)	5.00×10^3 m^3
Glass fibre, at plant (RER)	2.62×10^6 kg
Aluminium, primary, at plant (RER)	5.20×10^5 kg
Chromium steel 18/8, at plant (RER)	3.56×10^6 kg
Reinforcing steel, at plant (RER)	2.37×10^7 kg
Copper, at regional storage (RER)	3.41×10^5 kg
Polyvinylchloride, at regional storage (RER)	1.59×10^5 kg
Wire drawing, copper (RER)	3.41×10^5 kg
Sheet rolling, chromium steel (RER)	3.56×10^6 kg
Sheet rolling, steel (RER)	2.37×10^7 kg
Disposal, concrete, 5% water, to inert material landfill (CH)	7.50×10^4 kg
Transport, freight, rail (RER)	3.53×10^6 tkm
Disposal, municipal solid waste, 22.9% water, to sanitary landfill (CH)	6.00×10^5 kg
Transport, lorry 16–32 t, EURO5 (RER)	7.23×10^6 tkm
Output materials from EcoInvent	Quantities and units
Heavy-water plant	*1 unit*

Table 10
CML-IA characterisation factors [47] used for the life-cycle impact assessments in this work.

CML-IA metric	Abbreviation	Normalised unit	Region
100-year global warming potential	GWP 100a	$kgCO_2(eq)$	GLO
Acidification potential	AP	$kgSO_2(eq)$	GLO
Eutrophication potential	EP	$kgPO_4^{3-}(eq)$	GLO
Steady-state ozone depletion level	ODP_{ss}	kgCFC-11(eq)	GLO
High NO_x photo-chemical ozone creation potential	High-NO_x POCP	$kgC_2H_2(eq)$	RER
Human toxicity potential (infinite time scale)	HTP_∞	kg1-,4-DCB(eq)	GLO
Freshwater ecotoxicity potential (infinite time scale)	$FAETP_\infty$	kg1-,4-DCB(eq)	GLO
Marine ecotoxicity potential (infinite time scale)	$MAETP_\infty$	kg1-,4-DCB(eq)	GLO
Terrestrial ecotoxicity potential (infinite time scale)	$TAETP_\infty$	kg1-,4-DCB(eq)	GLO

To the best of our knowledge, the extraction of thorium from monazite has not previously been covered by an LCA. Data from an environmental impact assessment for a proposed monazite extraction facility in Australia has been used to provide input quantities of chemicals, water and output residues to landfill [27]. Input energy requirements have been adopted from EcoInvent's LCA for bastnasite production in China [24] and scaled by a factor of 0.01, as posited by the net energy analysis for bastnasite and monazite production in Ref. [28]. Similarly, carbon dioxide emissions and waste heat have also been scaled in the same way, as emissions data was not available. The materials required for extracting thorium dioxide from monazite processing are shown in Table 5.

2.6. Stage 3: Fuel fabrication

The fuel fabrication stage traditionally involves the conversion of UF_6 to UO_2, sintering UO_2 (and ThO_2) to form fuel pellets, encapsulating the fuel pellets into a fuel rod, and arranging the fuel rods to form a fuel assembly. The GT-MHR differs as UO_2 and ThO_2 are made into micron-sized kernels that are encased in four layers of three isotropic materials. The four layers are: a porous buffer layer made of carbon; a dense inner layer of pyrolytic carbon (PyC); a ceramic layer of silicon carbide; and a dense outer layer of PyC. The resulting tristructural-isotropic (TRISO) fuel particles are then encased in graphite to form a fuel compact. The quantities of materials in the finished fuel assemblies (plus other structural materials) that comprise the core of each reactor technology are presented in Table 6. For the EPR benchmark, values from Ref. [29] were taken.

In Ref. [16] the fuel fabrication process for the benchmark EPR was taken from Ref. [18]. This in turn takes into account a number of approximations due to the limited information available on the conversion of zircon to zirconium metal and its corresponding alloying to form zircaloy. From an LCA perspective, chromium metal was used as a proxy for zirconium. It is noted in Ref. [30] that the process energy of chromium (590 GJ/t_{pr}) is significantly lower than that of zirconium (1610 GJ/t_{pr}). In this work, we have used the same chromium approximation for zircaloy but have added an additional 80 MWh electricity consumption per kg fuel generated as an upper estimate of electricity requirements. Furthermore, in Ref. [18], burnable poisons, such as Gd_2O_3 and Er_2O_3, were not accounted for. In this work, it is assumed that 25% of the assemblies contain 8% Gd_2O_3which arises from the 18-month fuel cycle in Ref. [31]. Life cycle inventory (LCI) data for the process "samarium europium gadolinium concentrate, 94% rare-earth oxide, at plant" were used as a proxy for burnable poisons.

For the Th–U-fuelled EPR, it has been assumed that a silicon-carbide composite would be used as the cladding material due to the high burn-up of the seed fuel. Currently, silicon-carbide composites are not commercially available as a fuel cladding material, due to difficulties in fabricating hermetically sealed fuel rods on an industrial scale and the lack of information

Table 11
Results of the life-cycle impact assessment (per kWh generated) of three Th–U-fuelled nuclear energy systems compared to a reference U-fuelled EPR. All impact factors are global with the exception of High-NO_x POCP which is considered over Europe. The nomenclature used for the metrics is outlined in Table 10.

CML-IA metric (per kWh)	EPR UO_2	EPR UO_2/ThO_2	AHWR UO_2/ThO_2	GT-MHR UO_2/ThO_2
GWP 100a [$kgCO_2(eq)$]	6.60×10^{-3}	6.86×10^{-3}	1.32×10^{-2}	1.07×10^{-2}
AP [$kgSO_2(eq)$]	4.67×10^{-5}	4.96×10^{-5}	6.79×10^{-5}	9.30×10^{-5}
EP [$kgPO_4^{3-}(eq)$]	4.46×10^{-5}	4.78×10^{-5}	5.29×10^{-5}	9.45×10^{-5}
High-NO_x POCP [$kgC_2H_2(eq)$]	1.99×10^{-6}	2.09×10^{-6}	3.03×10^{-6}	3.95×10^{-6}
ODP_{ss} [kgCFC-11(eq)]	5.25×10^{-10}	5.57×10^{-10}	1.17×10^{-9}	1.01×10^{-9}
HTP_∞ [kg1-,4-DCB(eq)]	6.94×10^{-2}	7.36×10^{-2}	6.88×10^{-2}	1.56×10^{-1}
$FAETP_\infty$ [kg1-,4-DCB(eq)]	1.37×10^{-2}	1.46×10^{-2}	1.48×10^{-2}	3.02×10^{-2}
$MAETP_\infty$ [kg1-,4-DCB(eq)]	2.85×10^{1}	3.03×10^{1}	3.29×10^{1}	6.13×10^{1}
$TAETP_\infty$ [kg1-,4-DCB(eq)]	2.25×10^{-4}	2.41×10^{-4}	2.51×10^{-4}	4.93×10^{-4}

on how silicon carbide behaves under certain accident conditions. Further details on the use of silicon carbide as a cladding material can be found in Ref. [32]. For simplicity, it is assumed that all zircaloy (density: 6.55 g/cm^3) is replaced with silicon carbide (density assumed to be 3.21 g/cm^3) and that all other materials, with the exception of burnable poisons, remain the same as for the benchmark U-fuelled EPR. From an LCA perspective, LCI datasets are available for silicon carbide but may differ for the SiC_f/SiC_m composites. In this study, the silicon-carbide LCI data from EcoInvent v2.2 is used [33], and the same fuel fabrication infrastructure and process energies are assumed as for the EPR benchmark.

The cladding used in the Th–U-fuelled AHWR is similar to that in the EPR benchmark, and so numbers are changed according to the assembly parameters in Ref. [34]. The AHWR contains nearly twice as many fuel bundles as the number of fuel assemblies in the EPR (444 cf. 241). Dimensionally, the AHWR fuel cluster is shorter than the EPR (4.3 m cf. 4.8 m) and has a smaller cross-sectional area (~109 cm^2 *cf.* ~458 cm^2) [35].

The GT-MHR fuel is significantly different to that of the other technologies. Input materials per kg of TRISO particles are taken from Ref. [36]. No information on process energy is listed, and as there are no current facilities producing such fuel on an industrial scale, the existing infrastructure and energy inputs for EPR fuel fabrication are assumed.

2.7. Stage 4: Reactor construction and decommissioning

Accurate estimates for all of the materials and process energies required for constructing and decommissioning each of the different reactor technologies has proven difficult to ascertain. The aggregated bill of materials for each of the reactor technologies is presented in Table 7.

For the EPR, the LCA model in Ref. [16] has been used, although the amounts of concrete and reinforcing steel has been upscaled by a factor of ~1.5 to match the quantities reported in the UK Generic Design Assessment [37]. Correspondingly, the process energies for constructing and decommissioning the reactor from [16] have also been upscaled.

For the AHWR, as construction estimates are not presently available, numerous proxies have been needed. An assumption of 280,000 m^3 has been made for the concrete. This is half the amount of concrete required to build Tarapur 3 & 4 (two PHWRs) as reported in Ref. [38]. We believe this is a reasonable estimate, given that the reactor building, turbine hall and other major buildings on the site layout for the AHWR have the same cross-sectional area as Tarapur 3. The amount of reinforcing steel required has also been taken from Ref. [38]. Additional steel requirements for reactor internals have been taken from a proposed 600 MW(e) UK Steam Generating Heavy Water Reactor (SGHWR) [39], with the steel

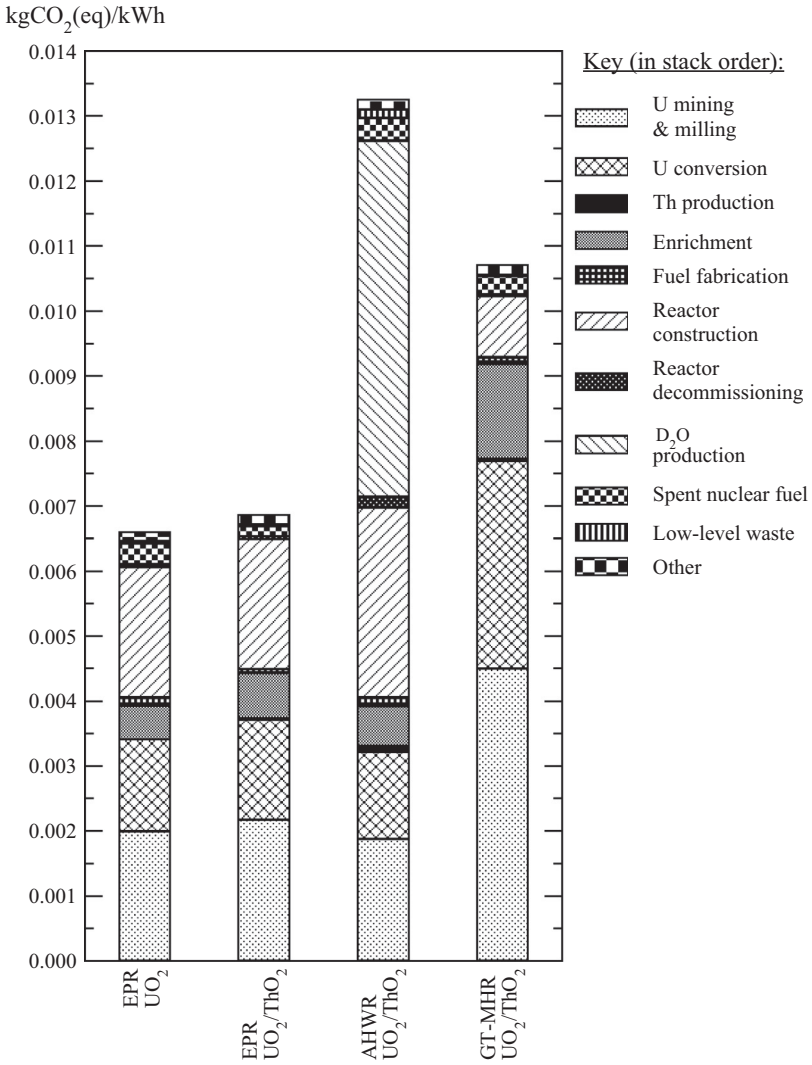

Fig. 4. Breakdown of the CML-IA metric "100-year Global Warming Potential (GWP 100a)" for each part of the nuclear fuel cycle for the four nuclear energy systems studied.

required for the turbine assumed to be the same as that used for the GT-MHR (see below). Estimates of the process energies for constructing and decommissioning the reactor have been scaled to the energy requirements for the EPR. The heavy water requirements for the AHWR are presented in Section 2.7.1.

For the GT-MHR, concrete requirements were based on scale drawings of the reactor building and site from Ref. [40] and are comparable to the estimates provided in Ref. [41]. Detailed designs for the steel requirements of the reactor pressure vessel and turbomachinery were taken from Refs. [40,42]. As for the AHWR, estimates of the process energies for constructing and decommissioning the reactor have been scaled to the requirements for the EPR. The initial helium requirements of 3800 kg, plus an assumed annual loss rate of 10% were taken from Ref. [43].

2.7.1. D_2O requirements for the AHWR

The AHWR uses heavy water (D_2O) to moderate the neutrons generated by fission, whereas light water, contained in pressure tubes, is used as the coolant. The heavy water inventory required for the AHWR (and associated losses per annum) are yet to be published. Therefore, the inventory for the 600 MW(e) UK prototype SGHWR of 162 tonnes has been assumed [39]. An assumed loss rate of 3.3% per annum, akin to the annual loss rate associated with a 220 MW(e) PHWR from Ref. [44], has been adopted.

Historically, a number of different processes have been used to generate heavy water. These are described in further detail in Ref. [45]. In this work, the Girdler-Sulfide (GS) process, as described in Ref. [45], has been assumed. The material requirements to generate 1 kg of heavy water are shown in Table 8. Infrastructure requirements were estimated from the decommissioning of part of the Bruce Heavy Water Plant [46] and are presented in Table 9, with the assumption that such a plant produces 800 metric tonnes per year and the plant life is 15 years.

2.8. Stages 5 & 6: Spent fuel repository and deep geological repository

Within this work, the Swiss NAGRA facility has been assumed, as described in Ref. [18] and adopted in Ref. [16]. It should be noted that the Swedish SKB-3 is currently the most up-to-date repository design. However, a complete LCA for the associated facilities (spent fuel storage, intermediate-level waste storage and disposition, and high-level waste disposition) was not publically available at the time this work was carried out.

3. Results

Results of the various life-cycle analyses that have been performed as part of this work are presented in the following sections. The life-cycle emissions per kWh generated from each of the four

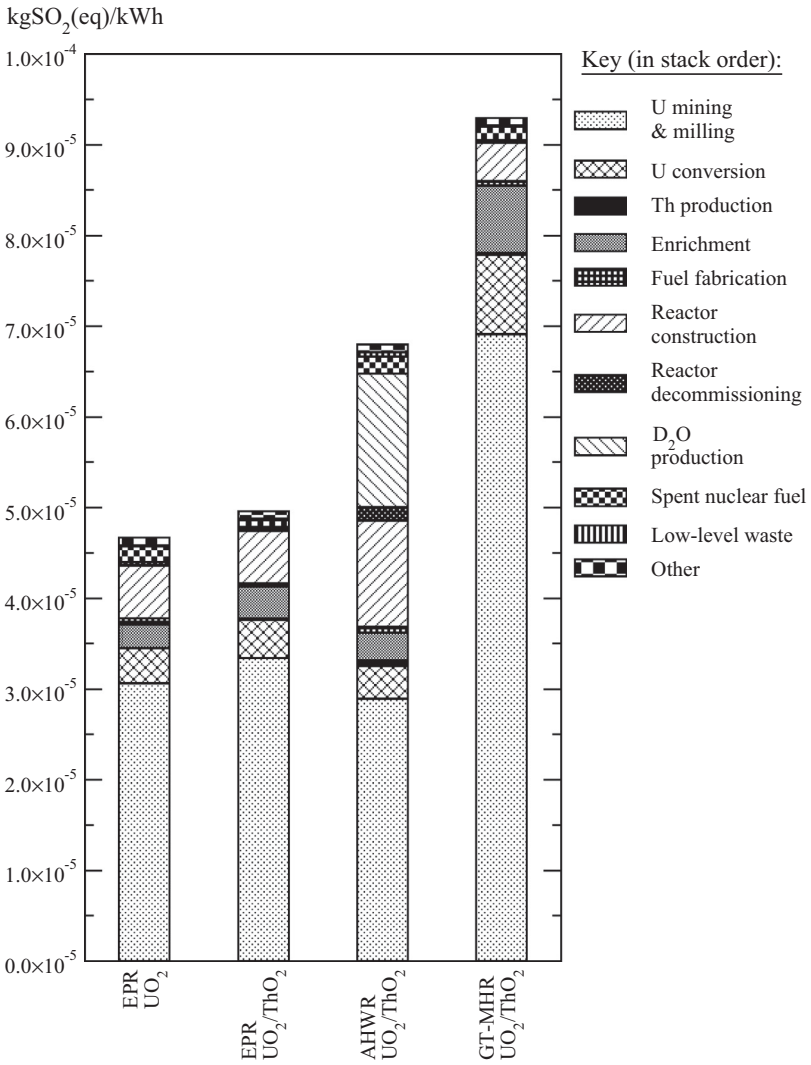

Fig. 5. Breakdown of the CML-IA metric "Acidification Potential (AP)" for each part of the nuclear fuel cycle for the four nuclear energy systems studied.

nuclear energy systems studied are shown in Section 3.1. The life-cycle emissions per kg of heavy water produced for the AHWR are presented in Section 3.2. The life-cycle emissions per kg of uranium obtained by open-pit mining, underground mining, and in-situ leaching, and per kg of thorium recovered from monazitic sands are presented in Section 3.3. CML-IA characterisation factors [47] have been used throughout this study. The nomenclature used for these factors is presented in Table 10. As mentioned in Section 2, the results contained within this Section for electricity generation comprise individual values for each stage of the nuclear fuel cycle (presented in graphical form) with a single value for each emission metric per kWh generated shown in tabular form.

3.1. Life-cycle emissions per kWh electricity generated

The results of the life-cycle assessment are summarised in Table 11. A breakdown of 100-year global warming potential, acidification potential, eutrophication potential and ozone depletion potential for the various stages of the nuclear fuel cycle for the four nuclear energy technologies analysed in this work is shown in Figs. 4–7. It is evident that the uranium-fuelled EPR has the lowest emissions per kWh generated of all technologies. This is predominantly due to the increased uranium ore requirement for both the Th–U-fuelled EPR and Th–U-fuelled GT-MHR, and the heavy water requirements of the Th–U-fuelled AHWR (as described further in Section 2.7).

In the broader context of non-nuclear electricity-generating technologies, and using the results of a UK-centric life-cycle analysis [48], as shown in Table 12, the global warming potential of these four nuclear technologies is comparable to off-shore wind, and is less than solar photovoltaics (PV), combined cycle gas turbines (CCGT) and coal. The acidification potential, eutrophication potential, and ozone depletion potential are also comparable to off-shore wind.

3.2. Life-cycle emissions per kg of heavy water generated

The calculated life-cycle emissions per kg of heavy water produced are presented in Table 13.

3.3. Life-cycle emissions per kg of thorium and uranium mined

The results for the life-cycle analysis of the four nuclear energy systems are based on uranium sources comprising 25% from open-pit mining, 25% from underground mining and 50% from ISL. All thorium is assumed to be recovered from REE processing of monazitic beach sands. To provide a comparison of these different mining/recovery techniques, the 100-year global warming potential,

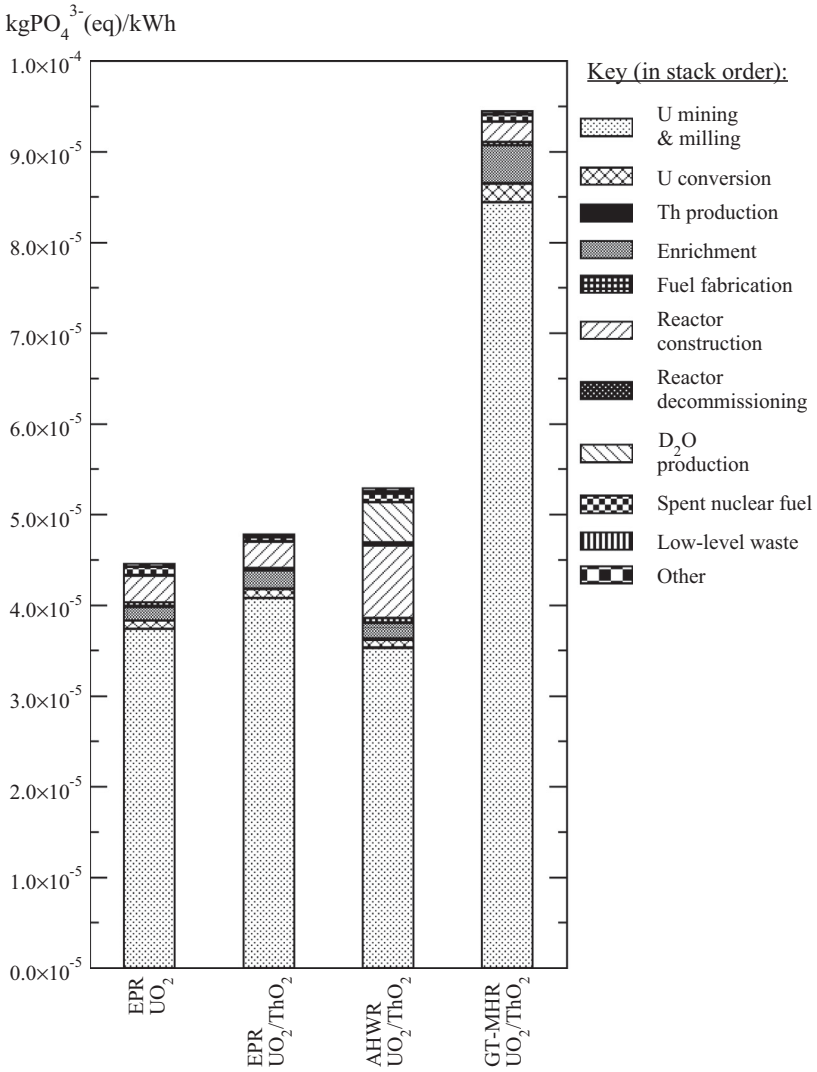

Fig. 6. Breakdown of the CML-IA metric "Eutrophication Potential (EP)" for each part of the nuclear fuel cycle for the four nuclear energy systems studied.

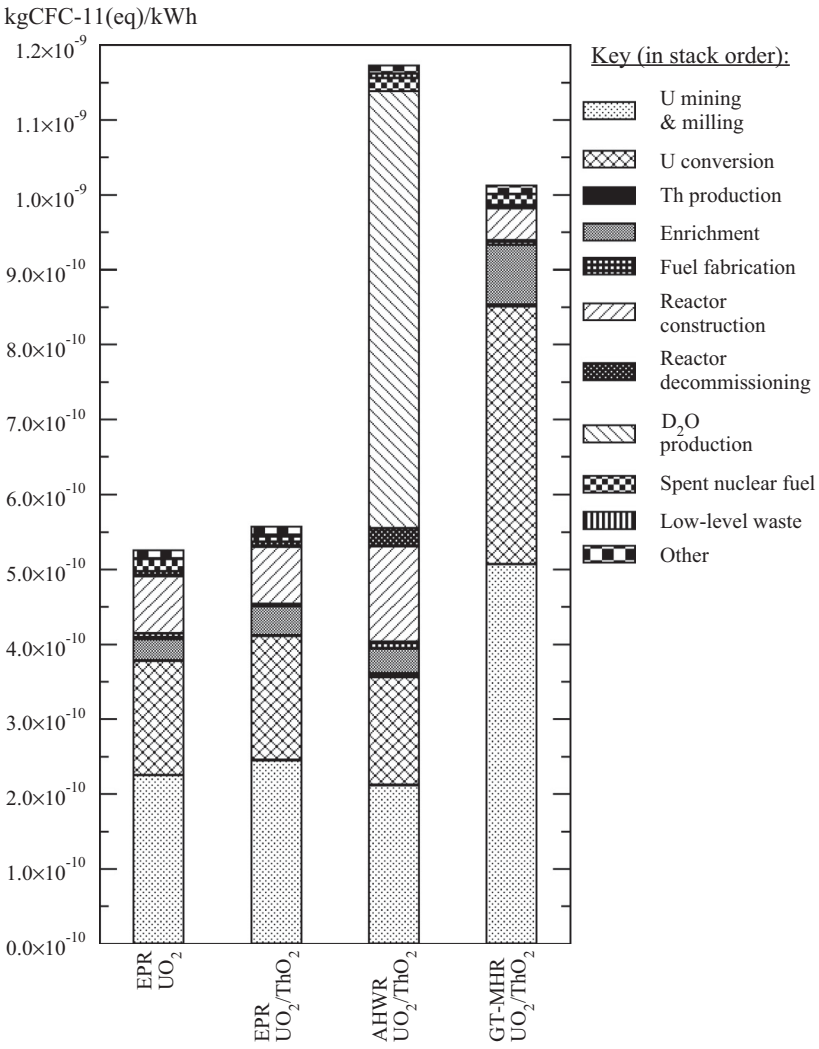

Fig. 7. Breakdown of the CML-IA metric "steady-state Ozone Depletion Potential (ODP_{ss})" for each part of the nuclear fuel cycle for the four nuclear energy systems studied.

Table 12
Comparison of selected results of the life-cycle impact assessment (per kWh generated) of the reference U-fuelled EPR in this work to the results of the life-cycle impact assessment for various electricity generating systems in the UK from Ref. [48]. The nomenclature used for the metrics is outlined in Table 10.

CML-IA metric	*This work*	Mid-point values for UK Electricity Generating Technologies from Ref. [48]				
(per kWh)	*EPR UO_2*	Pulverised Coal	CCGT	Nuclear (Gen II PWR)	Offshore Wind	Solar PV
GWP 100a [$kgCO_2$ (eq)]	6.60×10^{-3}	1.07×10^{0}	3.79×10^{-1}	6.24×10^{-3}	1.12×10^{-2}	8.78×10^{-2}
AP [$kgSO_2$ (eq)]	4.67×10^{-5}	1.78×10^{-3}	1.48×10^{-4}	4.40×10^{-5}	8.29×10^{-5}	4.36×10^{-4}
EP [$kgPO_4^{3-}$(eq)]	4.46×10^{-5}	2.15×10^{-4}	6.23×10^{-5}	1.32×10^{-5}	6.01×10^{-5}	6.87×10^{-5}
ODP_{ss} [kgCFC-11]	5.25×10^{-10}	4.25×10^{-9}	1.27×10^{-8}	5.41×10^{-10}	5.96×10^{-10}	1.75×10^{-8}

Table 13
Results of the life-cycle impact assessment for the production of 1 kg of heavy water by the GS process. The nomenclature used for the metrics is outlined in Table 10.

CML-IA metric (per kg D_2O)	Quantity
GWP 100a [$kgCO_2$(eq)]	1.66×10^{3}
AP [$kgSO_2$(eq)]	4.45×10^{0}
EP [$kgPO_4^{3-}$(eq)]	1.35×10^{0}
ODP_{ss} [kgCFC-11(eq)]	1.76×10^{-4}
High-NO_x POCP [kgC_2H_2(eq)]	2.32×10^{-1}
HTP_∞ [kg1-,4-DCB(eq)]	5.65×10^{2}
$FAETP_\infty$ [kg1-,4-DCB(eq)]	2.21×10^{2}
$MAETP_\infty$ [kg1-,4-DCB(eq)]	8.18×10^{5}
$TAETP_\infty$ [kg1-,4-DCB(eq)]	8.88×10^{0}

acidification potential, eutrophication potential, and steady-state ozone depletion potential per kg of uranium (as heavy metal) and per kg of thorium (as heavy metal) are shown in Fig. 8 and Table 14.

4. Discussion

The nuclear fuel cycle is a global enterprise. The facilities associated with Stages 1–6 in Fig. 1 are located all over the world, and very few countries have all of these stages of the nuclear fuel cycle located within their borders. Therefore, there are risks that by aggregating all of the processes to yield a single indicator highly localised detriments may be overlooked. This is true for all electricity generation technologies reliant on materials extracted and

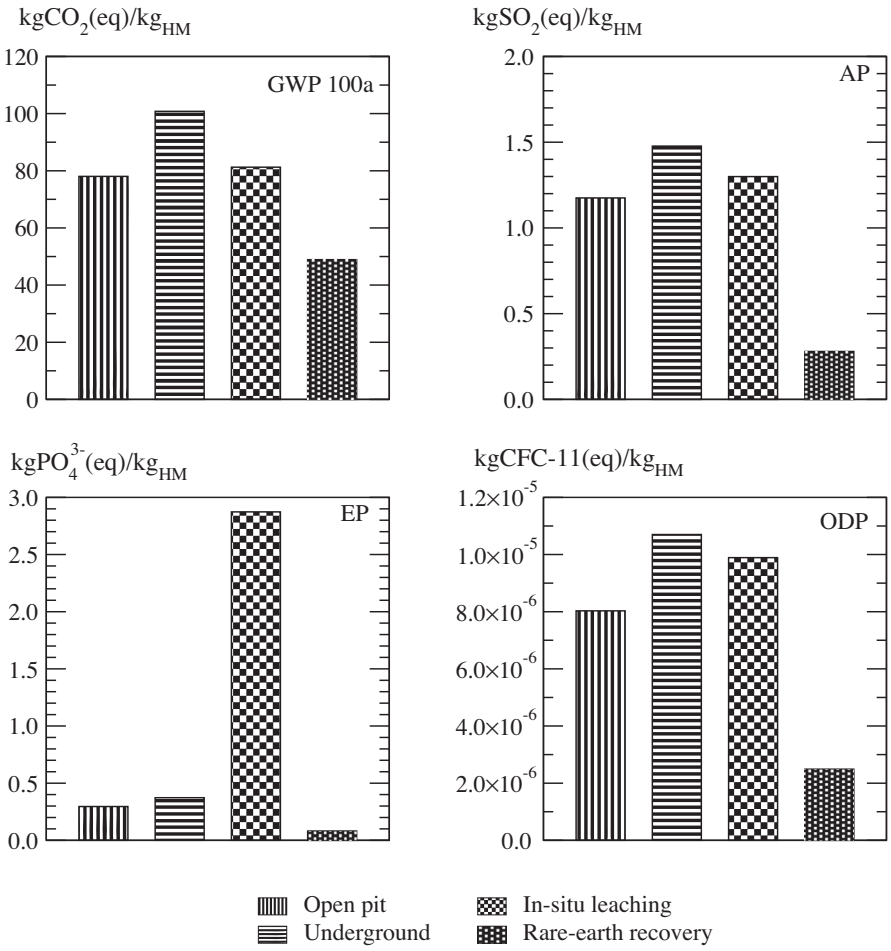

Fig. 8. Comparison of "100-year Global Warming Potential (GWP 100a)", "Acidification Potential (AP)", "Eutrophication Potential (EP)", and "steady-state Ozone Depletion Potential (ODP)" for uranium mined via open-pit mining, underground mining and ISL and thorium recovered from REE processing of monazitic beach sands.

components fabricated over the world. However, the majority of atmospheric emissions are considered transboundary and can be considered of global importance, most notably carbon dioxide emissions and their relation to anthropogenic climate change, with countries aiming to limit their emissions either as part of the Kyoto process [49] or other directives (such as the 20% reduction in emissions across Europe in EC Directive 2009/29/EC [50]). Transboundary air pollution acts such as the "Gothenburg Protocol" [51] and EC Directive 2001/81/EC [52] limit national emissions with a specific focus on acidification and eutrophication. Historically, ozone depletion has been of significant concern, with the Montreal Protocol being adopted to limit the amount of trading and consumption of ozone depleting substances [53]. Hence, emphasis is placed here on these particular emissions. The remaining indicators surrounding toxicity potentials are included for completeness and can be used to compare the relative performance of these systems.

The decarbonisation of today's energy mix is a significant goal in today's global energy policy. Nuclear energy is often described as a low-carbon source of electricity. However, various meta-analyses of nuclear energy have provided a significantly diverse range of CO_2(eq) emissions, including 10–130 gCO_2(eq)/kWh (mean 65 gCO_2(eq)/kWh) in the comprehensive net energy analysis by Lenzen [54], 1.4–288 gCO_2(eq)/kWh (mean 66 gCO_2(eq)/kWh) in the meta-analysis by Sovacool [55].

In this study, the range of estimated CO_2-equivalent life-cycle emissions for the four nuclear energy systems is 6.6–13.2 gCO_2(eq)/kWh is at the lower end of the estimates in Lenzen's and Sovacool's studies. We suggest four reasons as to why these emissions are comparatively low relative to the aforementioned meta-studies. First, today's enrichment market is almost exclusively comprised of gas-centrifuges. Meta-analyses of earlier nuclear energy technologies would have contained nuclear fuel enriched by gaseous diffusion, a process that had significantly greater energy requirements than centrifuge enrichment (~2500 kWh_{el}/SWU cf. ~50 kWh/SWU) [18]. Second, the unit size of earlier nuclear energy technologies was lower than present technologies, i.e. the increased plant size has lower requirements of construction materials per MW installed than earlier technologies. Third, the capacity factors of existing nuclear power plants have significantly increased, e.g. the average availability of the US fleet has increased from ~70% in 1990 to ~90% in 2005 [56]. Fourth, the results of life-cycle assessments for nuclear power plants based on EcoInvent v2.2 are observed to be at the lower end of emissions' estimates, e.g. Ref. [16].

We note that a number of processes have heavily relied on assumptions and sensitivity testing the vast number of processes included in these models is non-trivial. For certain approximations, especially for ISL of uranium and the production of zircaloy for the cladding, detailed LCA analyses are needed. A comprehensive LCA process is also required for discharged fuel from the reactor that is ultimately destined for an SKB-type repository. The results of 4D CAD-based project management software could also significantly improve the estimates of the energies required to construct

Table 14
Results of the life-cycle impact assessment for the production of 1 kg of uranium (as heavy metal) by open-pit mining, underground mining, and ISL; and for the production of 1 kg of thorium (as heavy metal) by REE processing. The nomenclature used for the metrics is outlined in Table 10.

CML-IA metric (per kg_{HM})	Open-pit	Underground	ISL	REE processing
GWP 100a [$kgCO_2$(eq)]	7.8×10^1	1.0×10^2	8.1×10^1	4.9×10^1
AP [$kgSO_2$(eq)]	1.2×10^0	1.5×10^0	1.3×10^0	2.8×10^{-1}
EP [$kgPO_4^{3-}$(eq)]	3.0×10^{-1}	3.7×10^{-1}	2.9×10^0	8.2×10^{-2}
$FAETP_\infty$ [kg1-,4-DCB(eq)]	8.6×10^2	8.6×10^2	1.5×10^2	1.2×10^1
HTP_∞ [kg1-,4-DCB(eq)]	4.7×10^3	4.8×10^3	5.8×10^2	2.7×10^1
$MAETP_\infty$ [kg1-,4-DCB(eq)]	1.6×10^6	1.7×10^6	4.1×10^5	4.2×10^4
High-NO_x POCP [kgC_2H_2(eq)]	4.5×10^{-2}	5.3×10^{-2}	3.9×10^{-1}	1.0×10^{-2}
ODP_{ss} [kgCFC-11(eq)]	8.0×10^{-6}	1.1×10^{-5}	9.9×10^{-6}	2.5×10^{-6}
$TAETP_\infty$ [kg1-,4-DCB(eq)]	1.7×10^1	1.7×10^1	1.1×10^{-1}	1.7×10^{-1}

and decommission the reactor. With that said, the single-value results for each stage of the nuclear fuel cycle show that such estimates would need to be orders-of-magnitude greater for them to have a noticeable impact on the overall life-cycle emissions.

From Tables 13 and Fig. 4, the heavy water requirements for the AHWR equate to 5.4 gCO_2(eq)/kWh. Using the results derived for the fleet of CANDU reactors in Ref. [57], with their assumption that fossil fuels were exclusively used for heavy-water production, the equivalent requirement would total 6.4 gCO_2(eq)/kWh. This implies that the energy requirements assumed in this work are slightly higher than those of Ref. [57], on the assumption that the UCTE grid used in this work comprises ~50% fossil fuels. Nevertheless the results are comparable.

From Fig. 8 and Table 14, ThO_2 extraction from REE processing has significantly lower emissions per kg extracted than the other types of extraction, although it should be stressed that the treatment of sulfidic and non-sulfidic tailings in this LCA model are coarse estimates. The assumed ThO_2 ore grade in monazite is 6% and is high compared with the average thorium content; however, for monazite with a significantly lower ore grade (e.g. 0.2%, a 30-fold decrease), assuming the same ThO_2 price and assuming that the allocation factor for rare-earth-oxides in monazite remains constant (i.e. the same rare-earth-oxide content and price), the emissions per kg of extracted ThO_2 would increase by only ~5%.

Figs. 4–7 highlight that the mining and milling stages generate the largest emissions for the nuclear energy systems analysed in this work. As shown by the example above, the decrease in ore grade is not inversely proportional to emissions per kg extracted and significantly depends on what is co-extracted. Towards 2030, it is expected that the price of uranium ore will remain low; hence, we expect the emissions associated with nuclear energy (per kWh generated) will remain low in the near-term future. An analysis of ore reserves that will become economically viable in the future is needed, in order to see how the emissions from nuclear power plants will change beyond 2030. It should be stressed that the emissions from mining and milling are highly localised, and such activities will consequently have greater detrimental effect in the areas surrounding these facilities. However, this statement is equally true for all electricity-generation technologies that require extracted materials or whose burdens are highly localised.

5. Conclusions

This paper has sought to investigate how life-cycle emissions would be affected by including thorium in the nuclear fuel cycle, and in particular its inclusion in technologies that could prospectively operate open Th–U-based nuclear fuel cycles. Three Th–U-fuelled nuclear energy systems operating with open nuclear fuel cycles were studied: (1) AREVA's EPR, (2) India's AHWR, and (3) General Atomics' (GT-MHR); and compared to a reference U-fuelled EPR also operating with an open nuclear fuel cycle. In the consequent life-cycle analysis, the reference U-fuelled system had the lowest overall emissions per kWh generated: i.e. 6.60 gCO_2 (eq)/kWh, 0.0467 gSO_2 (eq)/kWh, 0.0446 gPO_4^{3-} (eq)/kWh, and 5.25×10^{-7} gCFC-11(eq)/kWh. The emissions from the Th–U-fuelled EPR were typically ~4–7% higher than the reference U-fuelled EPR. Emissions from the Th–U-fuelled AHWR, and the Th–U-fuelled GT-MHR were typically ~20–100% higher than the reference U-fuelled EPR. The results highlighted that the requirement for mined or recovered uranium (and thorium) ore was the greatest overall contributor to emissions, with the possible exception of nuclear energy systems that require heavy water. From Ref. [11], the three Th–U-based systems considered offered negligible savings in terms of uranium ore and had enhanced separative work requirements per kWh generated which contributed to the greater emissions. The calculated emissions for recovering 1 kg of thorium from monazitic beach sands are 49 $kgCO_2$(eq)/kWh, 0.28 $kgSO_2$ (eq)/kWh, 0.082 $kgPO_4^{3-}$ (eq)/kWh, and 2.5×10^{-6} kgCFC-11(eq)/kWh. In terms of like-for-like comparison of mining and recovery techniques, thorium from monazitic beach sands had lower overall emissions than uranium that was either conventionally mined or recovered from ISL. With that said, monazitic beach sands (and equivalent placer deposits) only form a fraction of the overall known thorium ore deposits. However, it is expected that such deposits would generally be utilised first if thorium becomes a viable nuclear fuel (and hence a commodity). The range of CO_2(eq) emissions from these four technologies appears to be low in comparison to the majority of electricity-generating technologies. Further work to assess accurately the impacts of novel mining techniques, the effects of diminishing ore grades, and the embodied and process energies used in constructing and decommissioning facilities in the nuclear fuel cycle will add further robustness to the claim that nuclear energy can yield electricity with low-carbon emissions.

Data availability statement

Proprietary data (from EcoInvent v2.2 database) and non-proprietary data (generated by the authors) were used in this work. The non-proprietary data are available at: <https://www.repository.cam.ac.uk/handle/1810/247949>.

Acknowledgements

This work is supported by the Engineering and Physical Sciences Research Council, EPSRC(UK), under Grant No. EP/I018425/1. We would like to acknowledge Dr. Andrew Simons at Paul Scherrer Institute (CH) for allowing us to use and modify the EPR LCA model and for his help and assistance. We would also

like to acknowledge Professor Adisa Azapagic and Dr. Laurence Stamford at the University of Manchester (UK) for helpful and insightful discussions about life-cycle analyses of electricity-generating technologies and nuclear energy systems. Furthermore, we would like to acknowledge Professor P.D. Krishnani and the Reactor Physics Design Division at the Bhabha Atomic Research Centre for insightful discussions regarding the AHWR, and the UK National Nuclear Laboratory for helpful discussions with regards to the nuclear fuel cycle.

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